

Low-Temperature Emission Control to Enable Fuel-Efficient Engine Commercialization

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**Oak Ridge National Laboratory
National Transportation Research Center**

**2017 U.S. DOE Vehicle Technologies Office
Annual Merit Review**

June 6, 2017

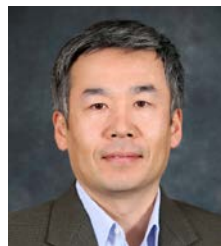
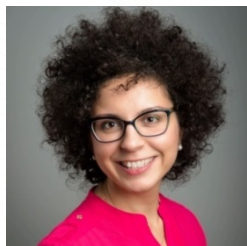
Project ID: ACS085

This presentation does not contain any proprietary, confidential, or otherwise restricted information



Acknowledgements

- ORNL Low Temperature Catalysis Team
 - Eleni Kyriakidou*, Andrew Binder, Jae-Soon Choi, James E. Parks



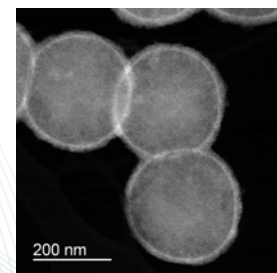
- DOE funding
 - Advanced Combustion Systems
 - Ken Howden, Gurpreet Singh, and Leo Breton



Energy Efficiency &
Renewable Energy

VEHICLE TECHNOLOGIES OFFICE

- Access to instrumentation
 - Micrographs and elemental maps captured using instrumentation (FEI Talos F200X S/TEM) provided by the Department of Energy, Office of Nuclear Energy, Fuel Cycle R&D Program and the Nuclear Science User Facilities



* - Eleni Kyriakidou is now an assistant professor in the Chemical and Biological Department at the University at Buffalo (SUNY)

Project Overview

Timeline

- Year 2 of 3-year program*

Budget

- FY2016: \$400k (Task 1*)
- FY2017: \$400k (Task 1*)

*Task 1: Low Temperature Emission Control

Part of large ORNL project “Enabling Fuel Efficient Engines by Controlling Emissions”
(2015 VTO AOP Lab Call)

Partners

- Low Temperature Aftertreatment Sub-Team of US DRIVE Advanced Combustion and Emission Control Tech Team
- Johnson Matthey
- Solvay
- NSF-funded scientists/students University of South Carolina
- Karlsruhe Institute of Technology

Barriers

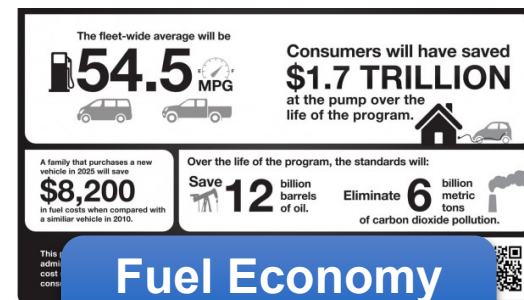
- From DOE Vehicle Technologies Multi-Year Program Plan
 - 2.3.1.B: Lack of cost-effective emission control
 - 2.3.1.D: Durability
- Overall, addressing emission compliance barrier to market for advanced fuel-efficient engine technologies

Objectives and Relevance

Develop new emission control technologies to enable fuel-efficient engines with low exhaust temperatures (<150°C) to meet emission regulations

Goal: 90% Conversion at 150°C

- Greater combustion efficiency lowers exhaust temperature
- Catalysis is challenging at low temperatures
- Emissions standards getting more stringent

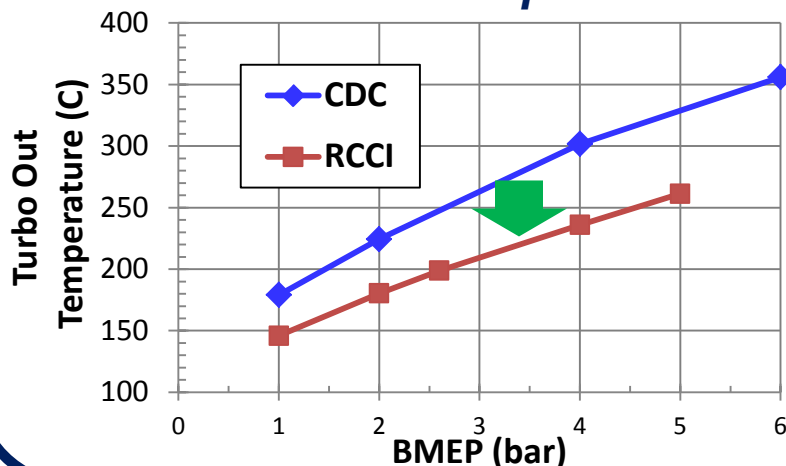


Fuel Economy Standards

54.5 mpg CAFE by 2025

Fuel Economy

Higher efficiency engines have lower exhaust temperatures*



* - Reactivity Controlled Compression Ignition (RCCI) [a Low Temperature Combustion mode] vs. Conventional Diesel Combustion (CDC)

Emissions

>70%
less
NO_x

>85%
less
NMOG

70%
less
PM

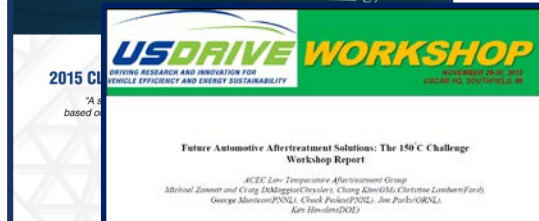
EPA Tier 3 Emission Regulations

2017-2025 (phased in)

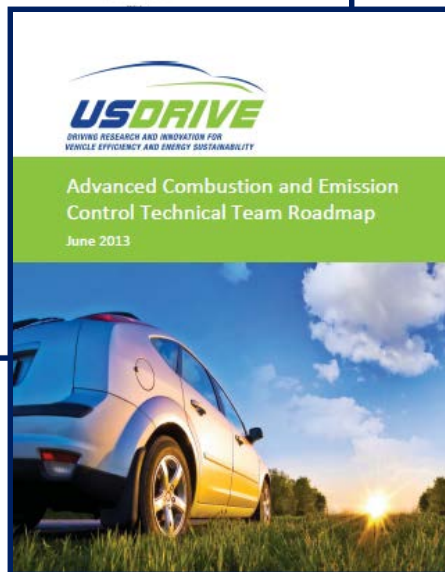
Relevance: Guiding Documents Define Needs



2015 CLEERS Industry Priorities Survey



USDRIVE "The 150°C Challenge" Workshop Report



USDRIVE ACEC Tech Team Roadmap (2013)

Identified Needs Addressed:

- Lower temperature CO and HC oxidation
- Low temperature NOx reduction
- Cold start emission trapping technologies
 - Especially passive NOx adsorbers
- Reduced PGM
- Better durability
- Promote innovative catalytic solutions via partnering with DOE BES programs

Relevant to all combustion approaches cited in ACEC Tech Team Roadmap

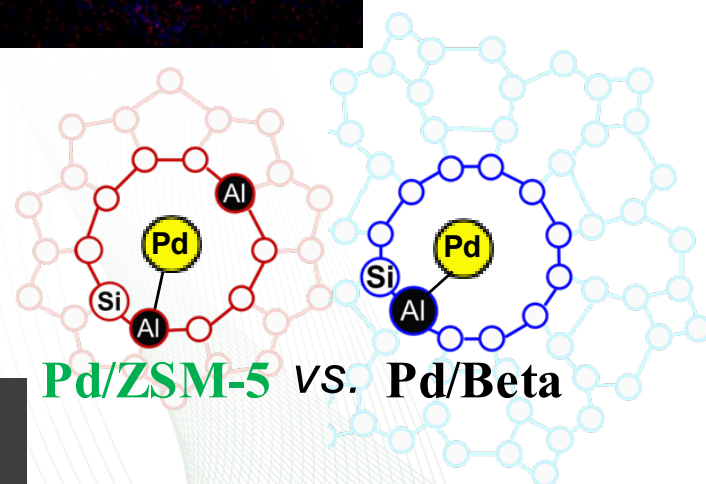
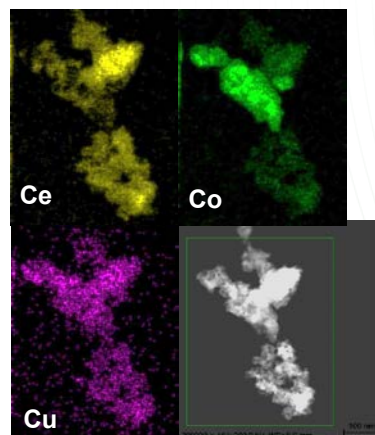
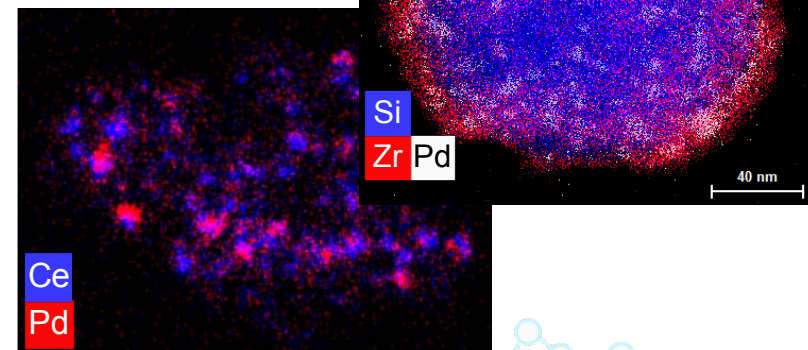
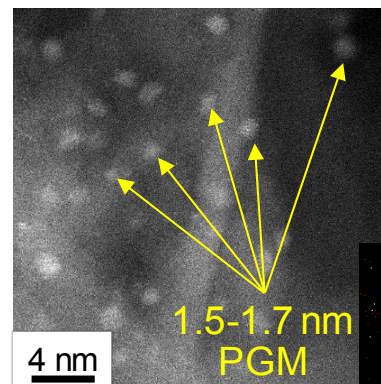
Low Temperature Combustion (LTC)

Dilute Gasoline Combustion

Clean Diesel Combustion (CDC)

Approach

- Advanced concepts through collaborations
 - Universities and BES-funded scientists
 - Evaluate promising materials w/ ACEC protocols
- Enhance conventional catalysts through support modifications
 - Maximize PGM usage and improve durability
 - Core@shell approaches with metal oxides
 - Targeted deposition PGM on nanoparticles of Ce- and Ce-Zr supported on alumina
- Passive adsorber/trap materials
 - Hold onto emissions until catalysts are active
 - Passive NO_x adsorbers
 - Hydrocarbon traps
- Novel materials (high risk)
 - PGM free metal oxides



Approach: employ low temperature protocols to evaluate novel catalysts

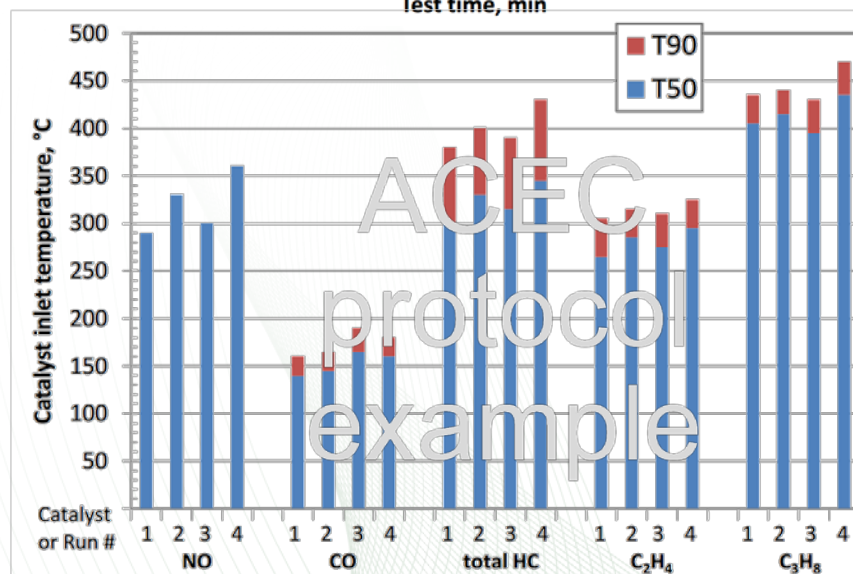
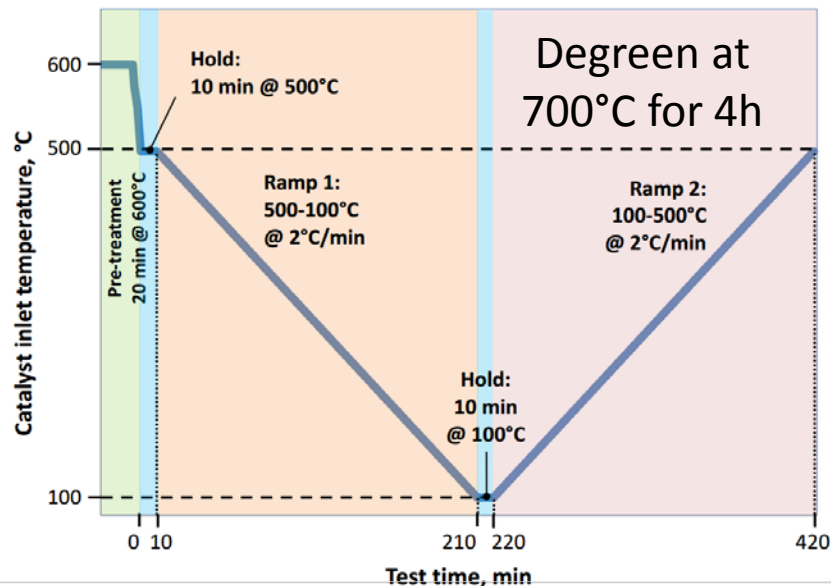
- Protocol finalized in June 2015 by the Low Temperature Aftertreatment Sub-Team of the US DRIVE Advanced Combustion and Emission Control Team
- Full file at: www.CLEERS.org

LTC-D: Low Temp. Combustion Diesel

Total HC₁: 3000 ppm
 C₂H₄: 1667 ppm
 C₃H₆: 1000 ppm
 C₃H₈: 333 ppm
 CO: 2000 ppm
 NO: 100 ppm
 H₂: 400 ppm
 H₂O: 6 %
 CO₂: 6 %
 O₂: 12 %
 Balance N₂

Powder Catalyst Requirements

- Reactor ID 3-13 mm
- Catalyst particle size ≤ 0.25 mm (60 mesh)
- Catalyst bed L/D ≥ 1
- Space velocity
 - 200-400 L/g-hr
 - For 0.1 g sample, flow 333-666 sccm



Approach: employ low temperature protocols to evaluate novel catalysts

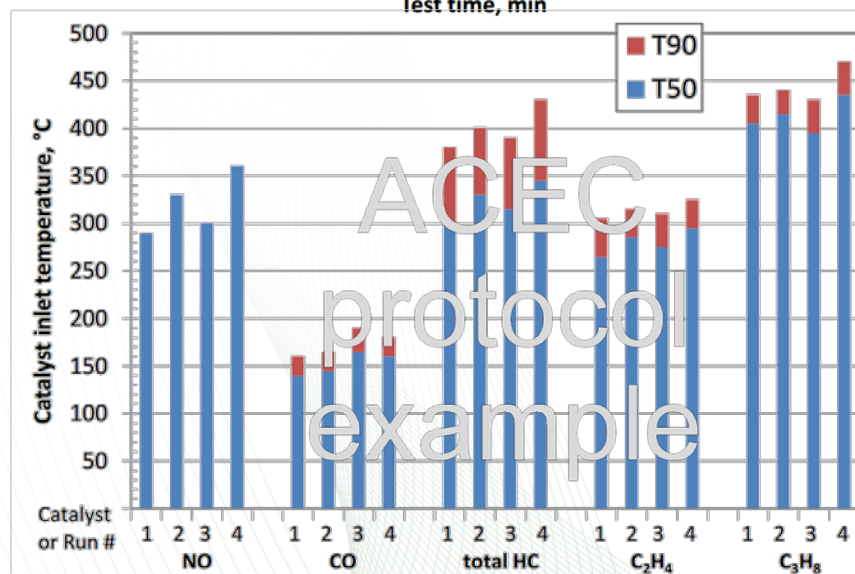
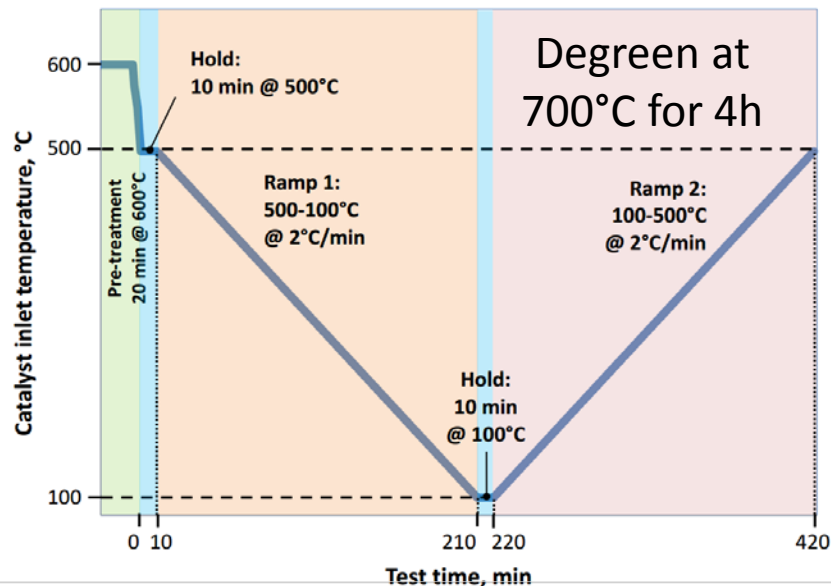
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LTC-D: Low Temp. Combustion Diesel

Total HC₁: 3000 ppm
 C₂H₄: 500 ppm
 C₃H₆: 300 ppm
 C₃H₈: 100 ppm
 *C₁₂H₂₆: **2100 ppm**
 CO: 2000 ppm
 NO: 100 ppm
 H₂: 400 ppm
 H₂O: 6 %
 CO₂: 6 %
 O₂: 12 %
 Balance N₂

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Collaborations

- **DOE Basic Energy Sciences Program**
 - Sheng Dai and Ashi Savara (ORNL), Center for Nanophase Material Science (ORNL)
- **CLEERS**
 - Dissemination of data; presentation at CLEERS workshop
- **Academia**
 - **University of South Carolina:** Professors John Regalbuto, Jochen Lauterbach and Erdem Sasmaz
 - **Karlsruhe Institute of Technology:** Professor Olaf Deutschmann and Andreas Gremminger
 - **University of Tennessee:** Professors Siris Laursen and Sheng Dai
- **Industry**
 - **USCAR/USDRIVE ACEC Low Temperature Aftertreatment (LTAT) Sub-Team**
 - low temperature evaluation protocols
 - **Catalyst and washcoat suppliers**
 - **Johnson Matthey:** Industry input from Haiying Chen
 - **Solvay:** alumina-based supports provided for PGM support studies at USC (Barry Southward)
- **Other DOE-funded FOA Projects**
 - **Ford-led project:** Next Generation Three-Way Catalysts for Future, Highly Efficient Gasoline Engines
 - Catalysts being investigated for stoichiometric applications
 - **UConn-led project:** Metal Oxide Nano-Array Catalysts for Low Temperature Diesel Oxidation

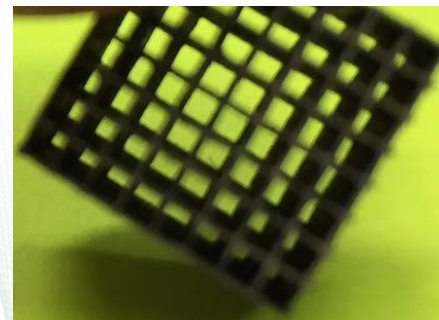
Milestones

- **FY16 Milestones:** *complete*

- Report on evaluation of CCC+PGM emissions control studies including implementation of full ACEC low temperature protocol (9/30/2016).
 - 2016 Annual Merit review
 - 2016 CLEERS Workshop
 - 2016 DOE Annual Report
 - Manuscript in preparation

- **FY17 Milestones:** *on track*

- Develop capability to washcoat novel powder catalysts (9/30/2017).
 - Initial coatings too thick
 - Second effort needed two dips to obtain CCC loading of 1-2 g/in³

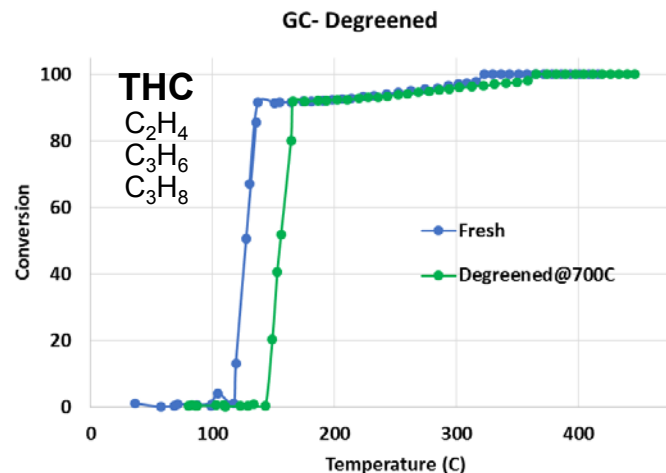
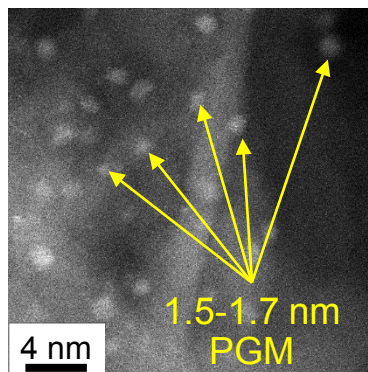


Summary of Technical Accomplishments

- ORNL/USC/Solvay Collaboration PGM/advanced supports
 - Series of Pt:Pd DOCs synthesized at USC (Univ. of South Carolina) on Solvay supports
 - Evaluated and aged at ORNL with ACEC protocols
 - 2% Pt on 80% Al₂O₃ / 20% SiO₂ shows promising results
- Enhance conventional catalysts through support modifications
 - Including Pt on both Ce/Zr nanoparticle approach and SiO₂@ZrO₂ core@shell catalysts greatly enhanced HC activity
 - Although Pt and Pd on same support did not yield benefit, physical mixtures of the two show promise
- Trapping materials
 - Expanded on Ag/zeolite studies to include Pd ion-exchanged materials
 - Pd/ZSM-5 catalyst shown to have good HC and NO_x trapping ability
 - Combining best trap and best DOC showed excellent low temperature behavior and sulfur tolerance
- PGM-free mixed metal oxides
 - Addition of Mn to CCC-based mixed metal oxide significantly improved high space velocity CO activity and sulfur tolerance

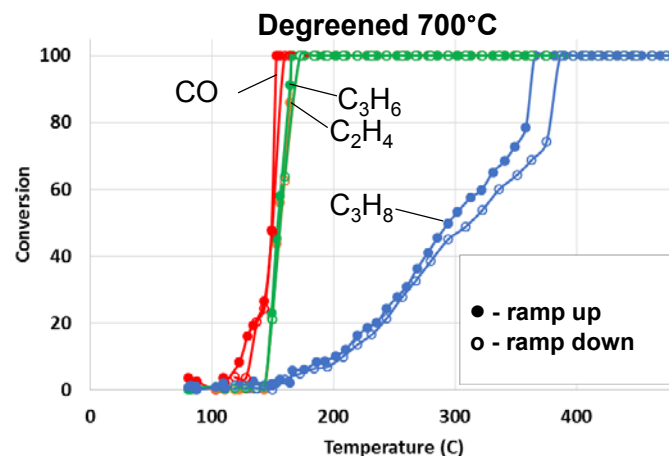
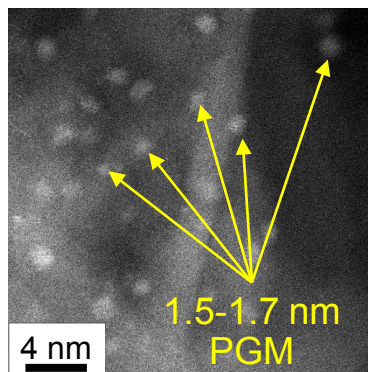
University of South Carolina (USC) and Solvay collaboration yielding promising results for stable PGM catalysts

- Prof. Regalbuto (USC) has been leading research on Strong Electrostatic Adsorption (SEA) of PGM on standard supports
 - Superb initial PGM dispersion
 - Durability has been an issue
- Solvay collaboration started
 - A leader in stable supports
 - Provided 7 supports
 - 70-100% Al, 0-30% Si, 0-4% La
- USC synthesis of Pt:Pd DOCs
 - Target PGM total: 2 wt%
 - Pt:Pd - 1:0, 3:1, 1:1, 1:3, 0:1
- Very promising results obtained with ACEC protocols
 - 2% Pt on 80% Al₂O₃ / 20% SiO₂

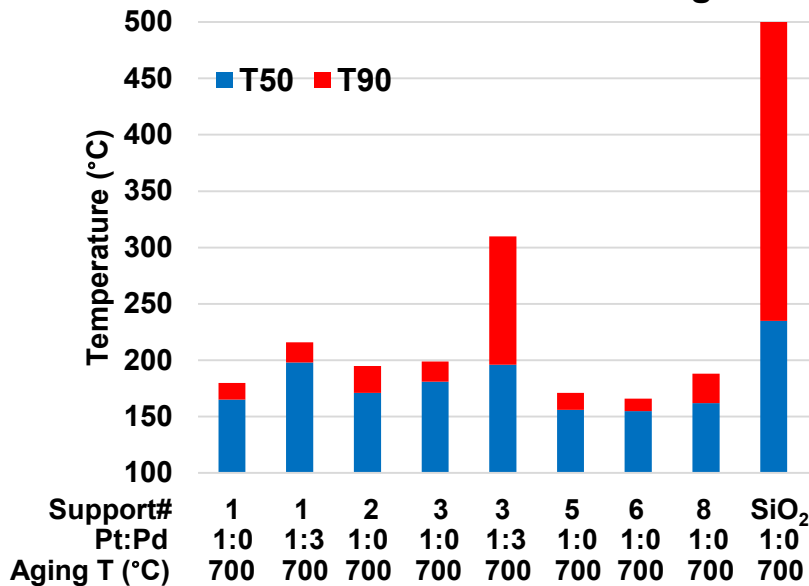


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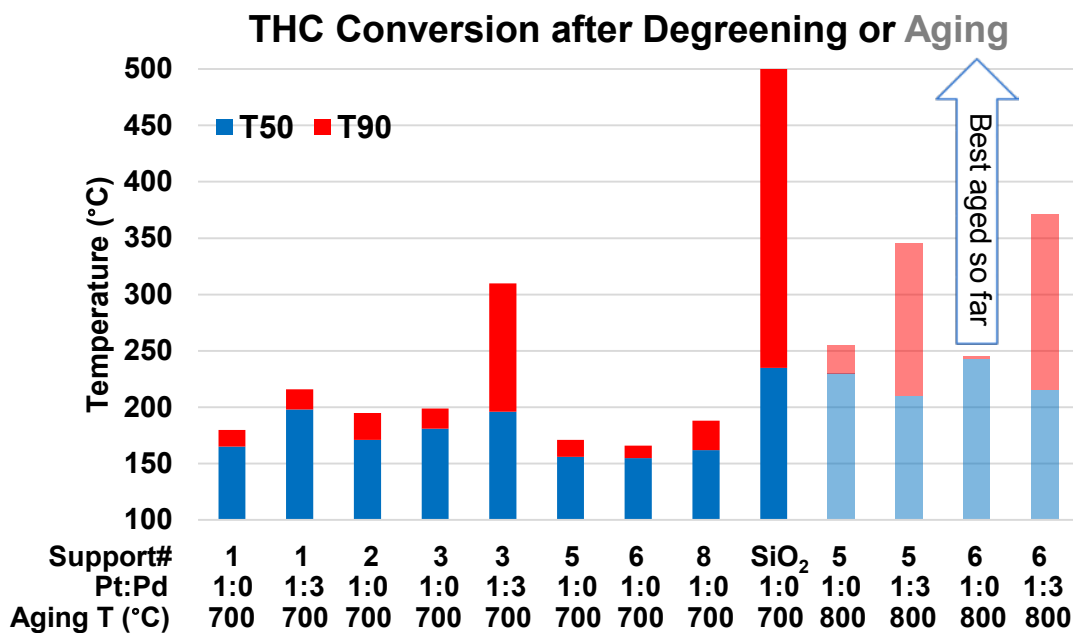
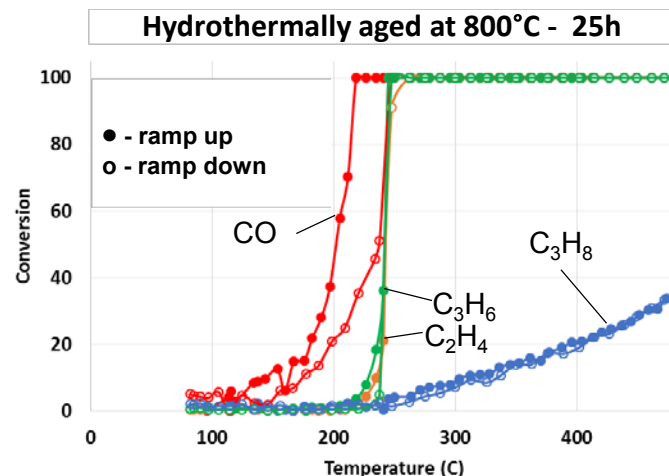
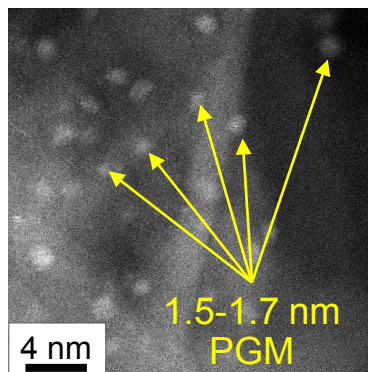


THC Conversion after Degreening or Aging



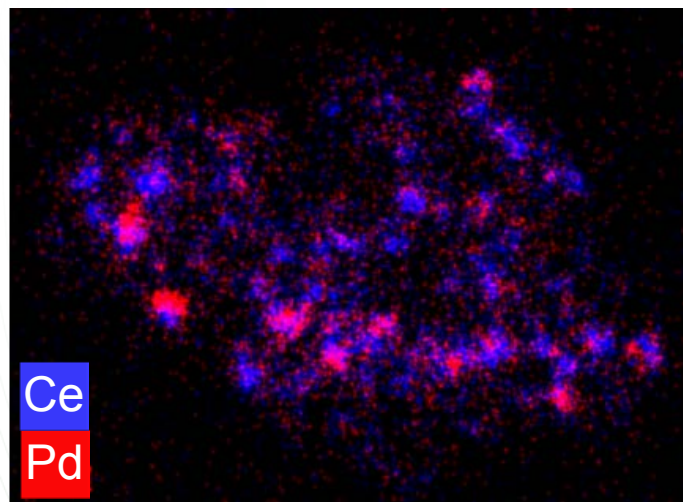
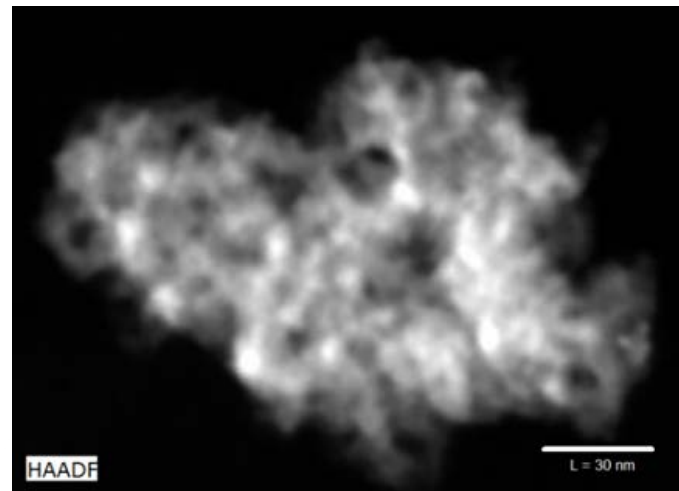
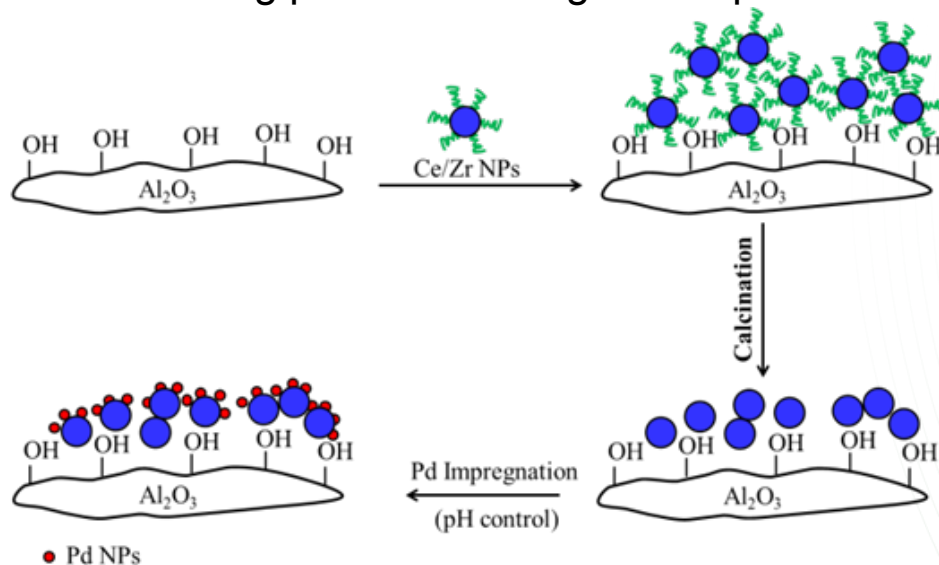
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 - Pt:Pd - 1:0, 3:1, 1:1, 1:3, 0:1
- Very promising results obtained with ACEC protocols
 - 2% Pt on 80% Al₂O₃ / 20% SiO₂
 - More samples to age



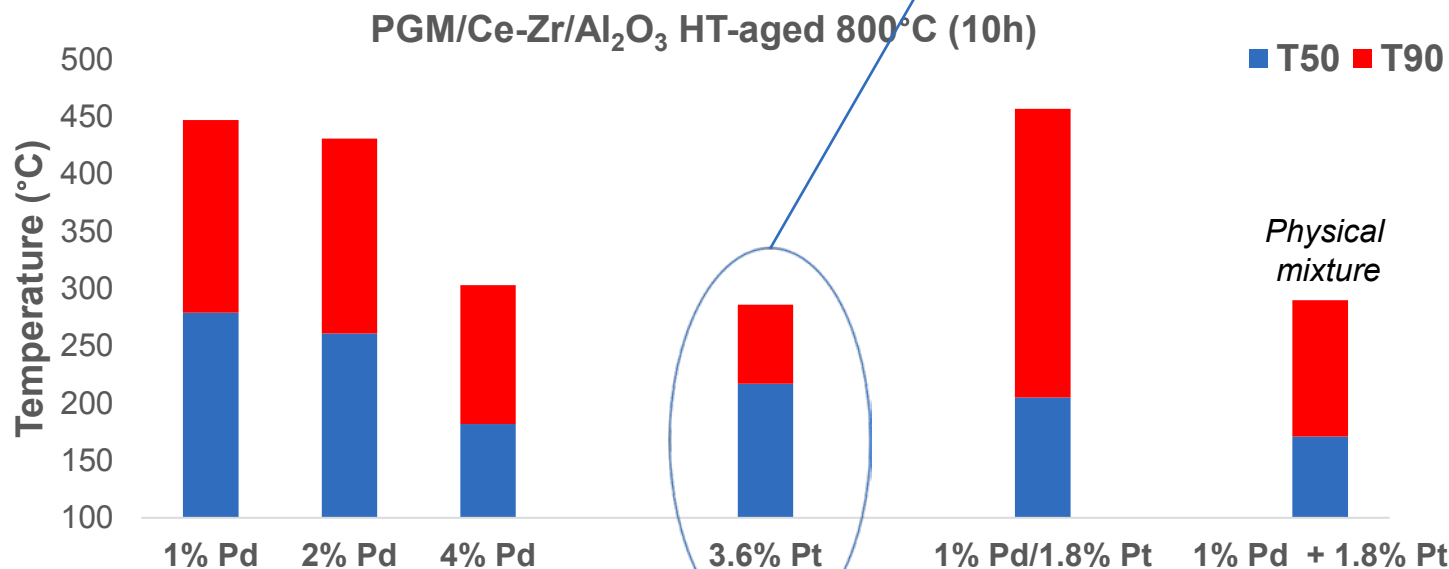
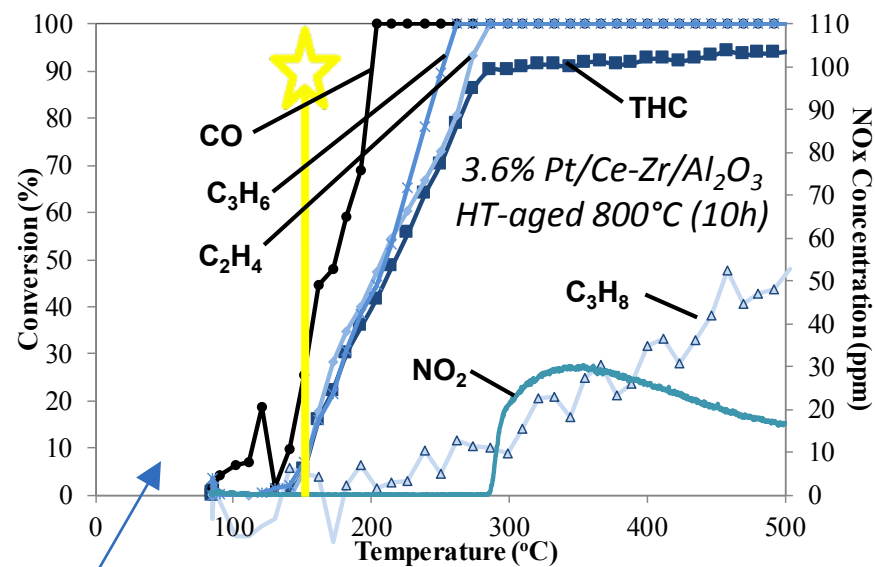
Targeted PGM deposition on nanoparticles of CeO_2 and $\text{CeO}_2\text{-ZrO}_2$ to improve durability and activity

- Starting with Ce or CeZr nanoparticles, ~5 nm, and anchor them to high surface area supports
 - In this instance Al_2O_3 , but SiO_2 also possible
- Target Pd or Pt deposition on preferred supported metal oxide
 - nano-particles of PGM on nano-particles of Ce-Zr
 - controlling pH enables targeted deposition



PGM/Ce-Zr/Al₂O₃ catalysts show promise, but best catalysts require high PGM content

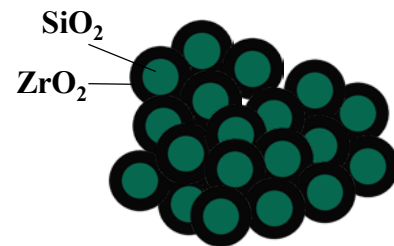
- Some promising results observed
 - Especially for Pt containing catalysts
 - HT-aged at 800°C data shown
- However, meeting 150°C target still challenging, especially C₃H₈
 - Interestingly, this material has better performance under S-GDI conditions*



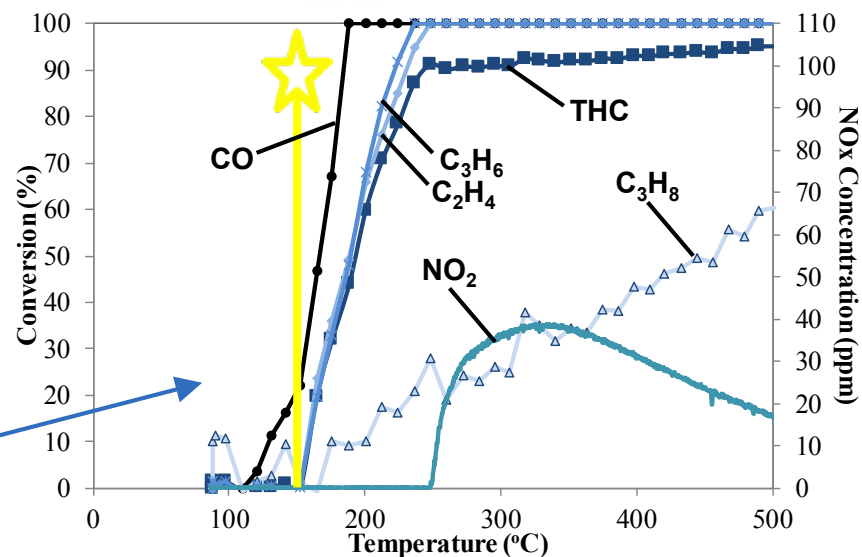
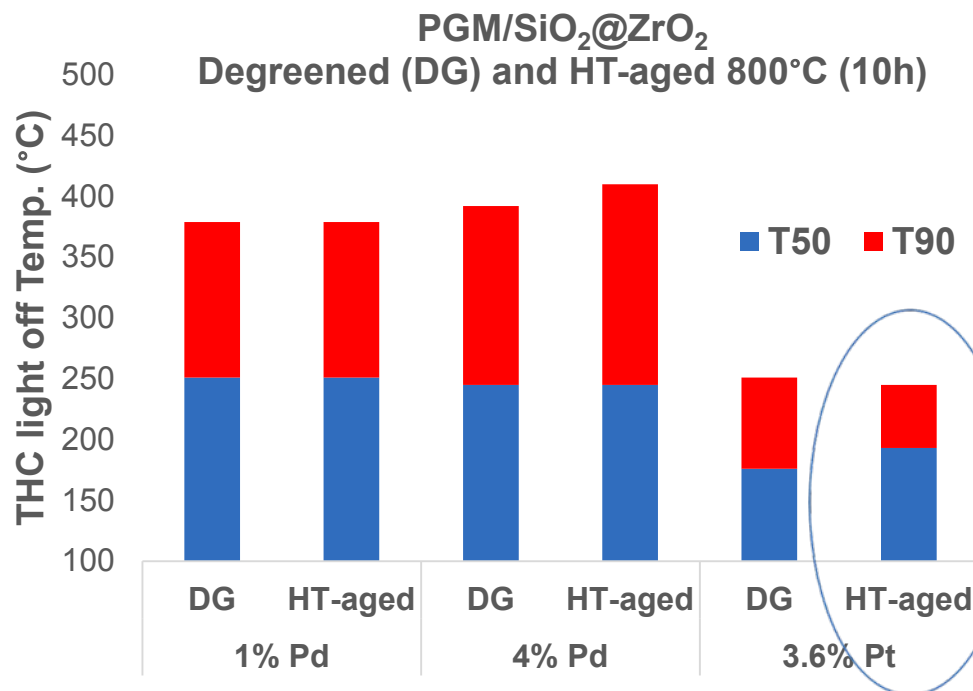
* - see results in PM-067, Thursday 11:30 AM

Novel synthesis technique successfully creates ZrO_2 shell around SiO_2 core

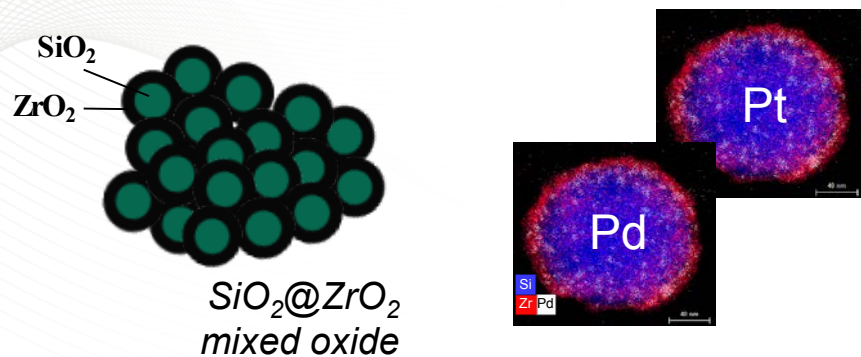
- Able to synthesize a complete ZrO_2 shell around SiO_2 core using novel technique
 - $\text{PGM}/\text{SiO}_2@\text{ZrO}_2$
 - PGM deposition solely on outer ZrO_2 shell
- While employing ACEC low temperature protocols improved activity shown with this technique
- Durable after aging at 800°C for 10h



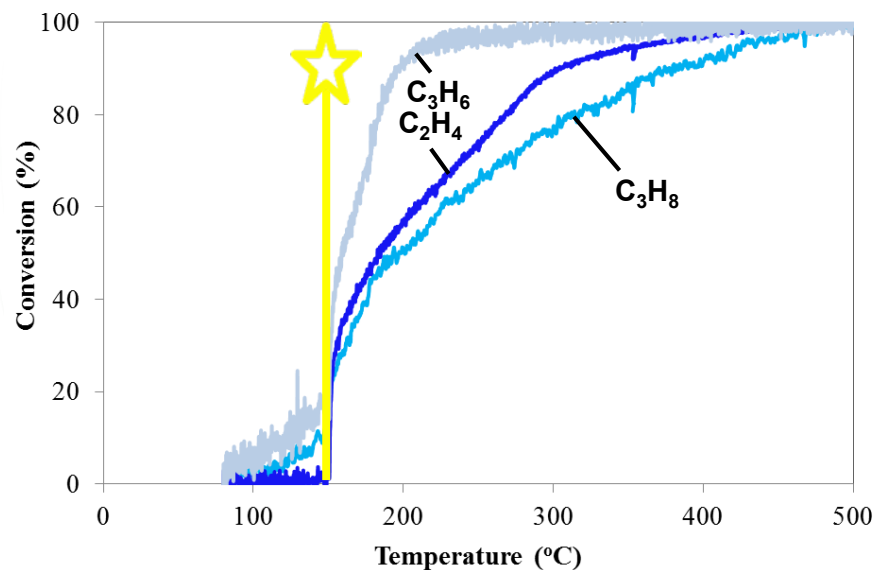
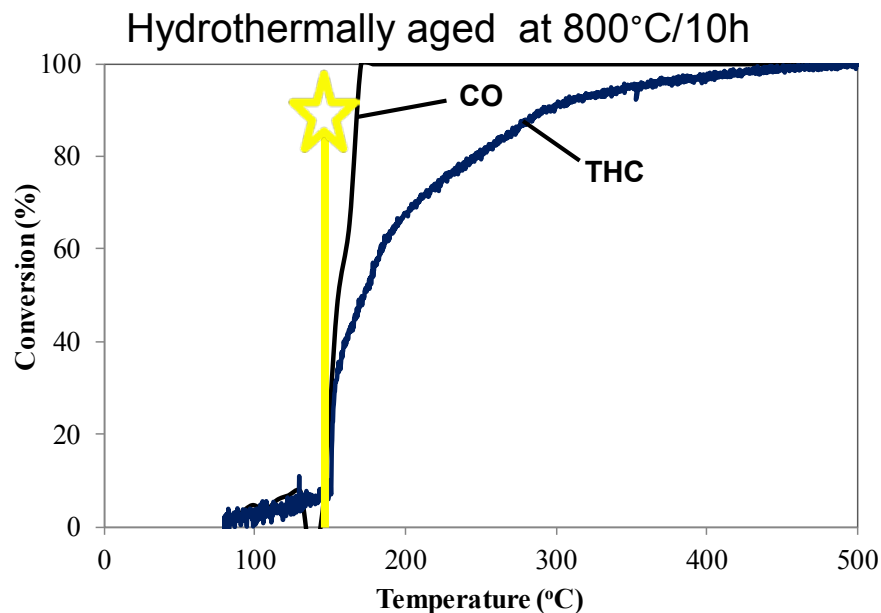
$\text{SiO}_2@\text{ZrO}_2$ mixed oxide



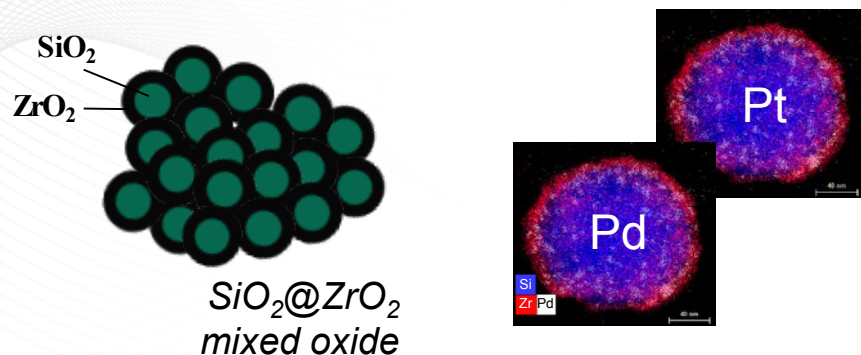
Core-shell concept has led to excellent activity in Pd + Pt physical mixture after HT-aging at 800°C



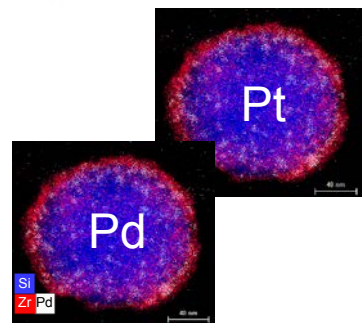
- PGM supported on a shell of ZrO_2 around a core of SiO_2 ($\text{SiO}_2@ZrO_2$)
- Exceptional low temperature activity observed with Pt+Pd physical mixture
 - Bed loading: 1.8% Pt and 1.0% Pd



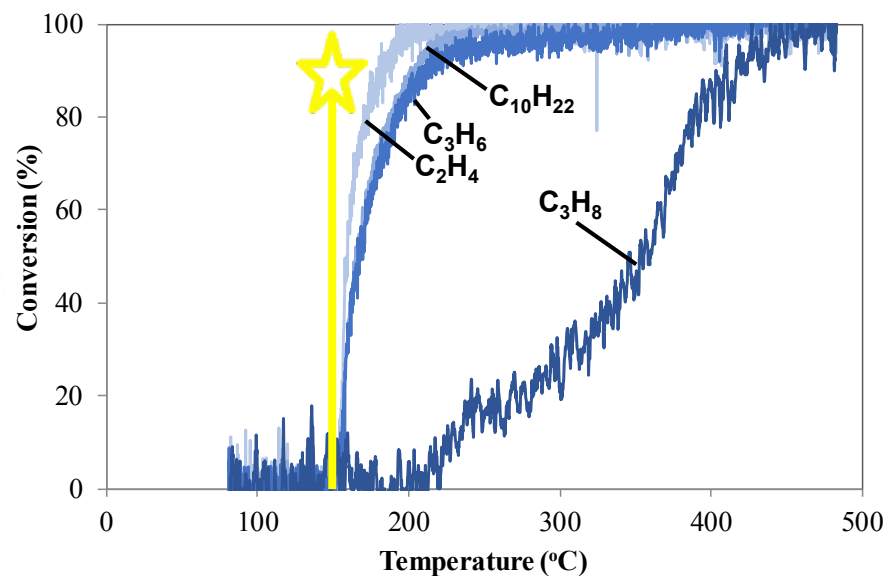
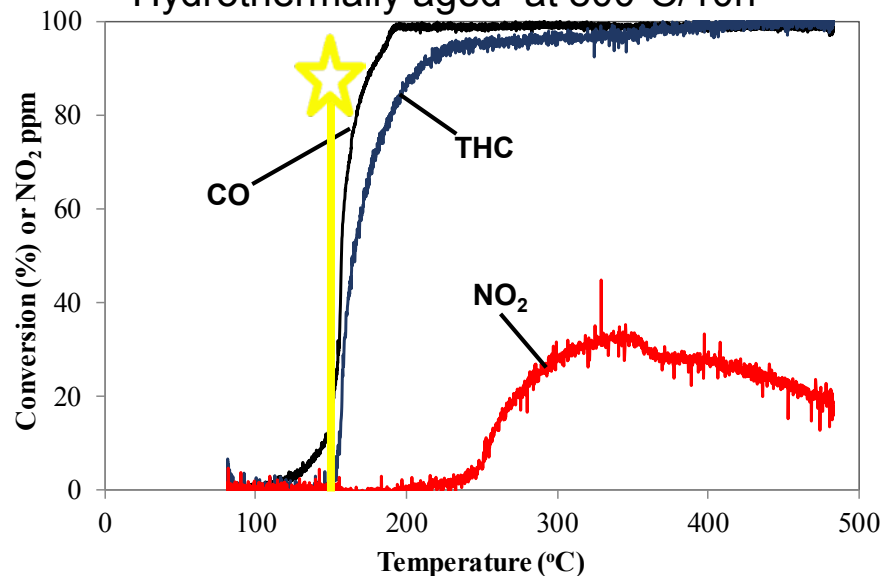
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- Exceptional low temperature activity observed with Pt+Pd physical mixture
 - Bed loading: 1.8% Pt and 1.0% Pd
- Also, active with liquid hydrocarbon LTC-D protocol using decane ($\text{C}_{10}\text{H}_{22}$)



Hydrothermally aged at 800°C/10h

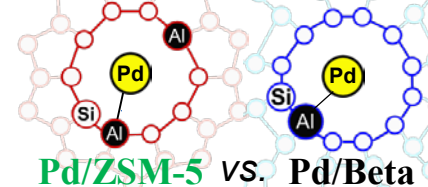


Pd/ZSM-5 catalyst has good HC and NOx trapping ability*

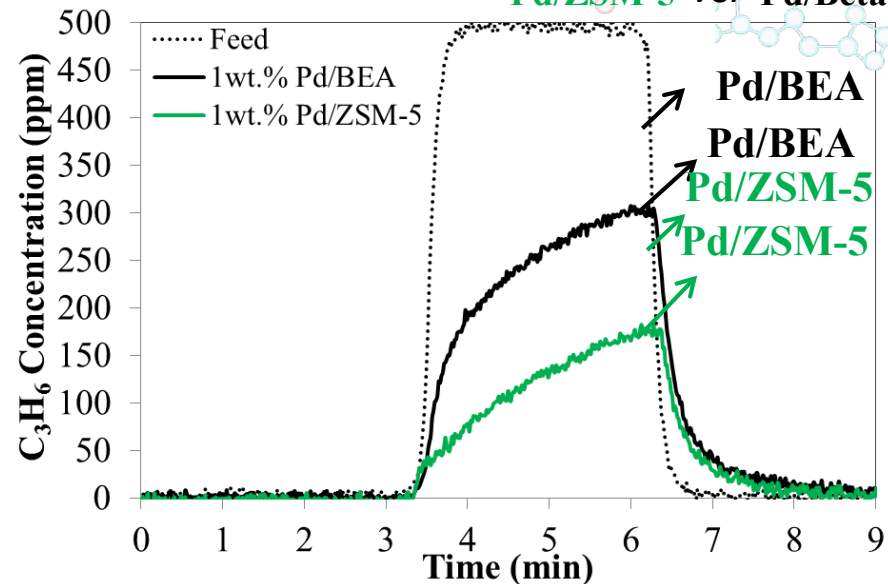
- ❖ C_3H_6 adsorption is sensitive to the type of metal.
- ❖ Pd/ZSM-5 shows the best C_3H_6 /NOx trapping ability.

Adsorption Conditions:

C_3H_6 : 167 ppm, 200 ppm NO, 10% O_2 , 5% H_2O ,
balance Ar, Total Flow: 600 sccm, SV: 90,000 h^{-1}



Adsorption



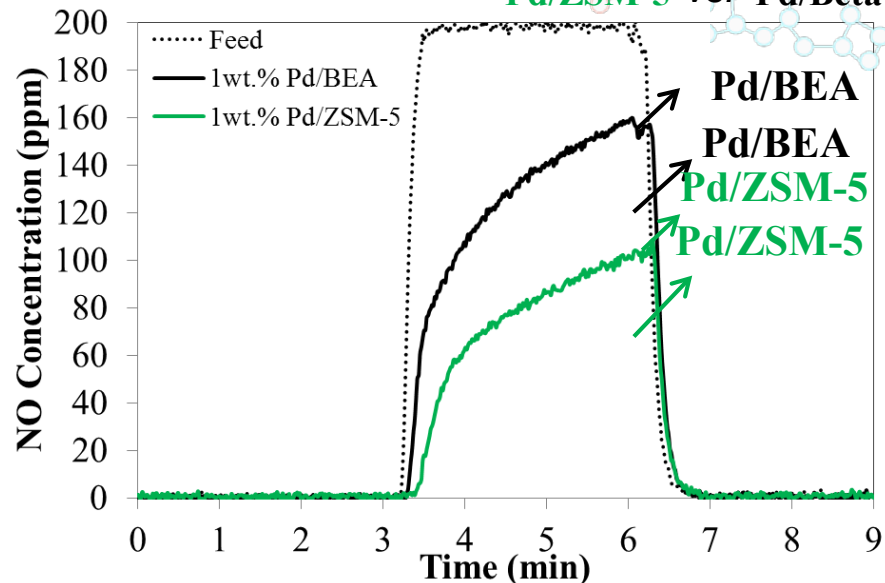
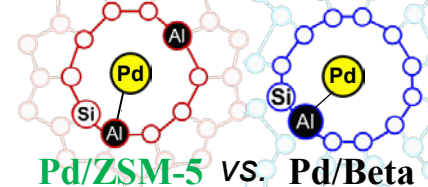
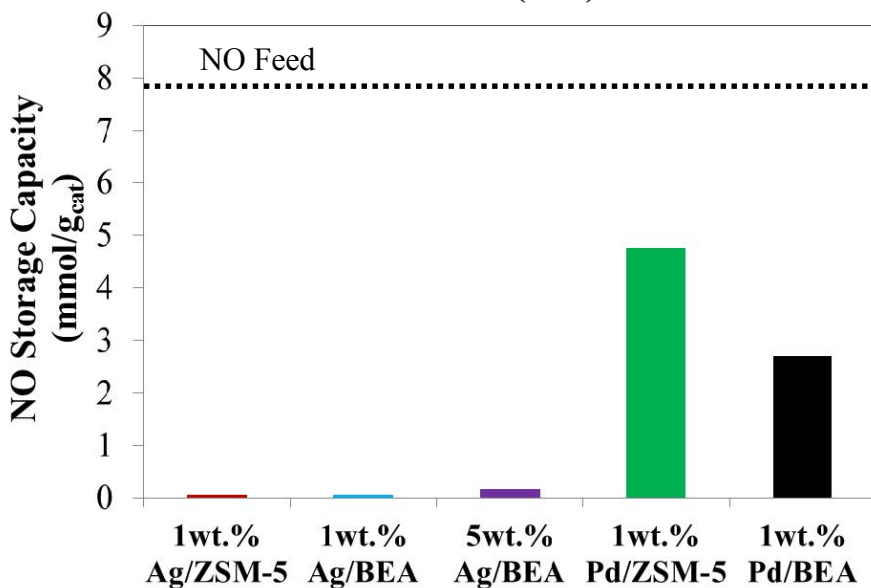
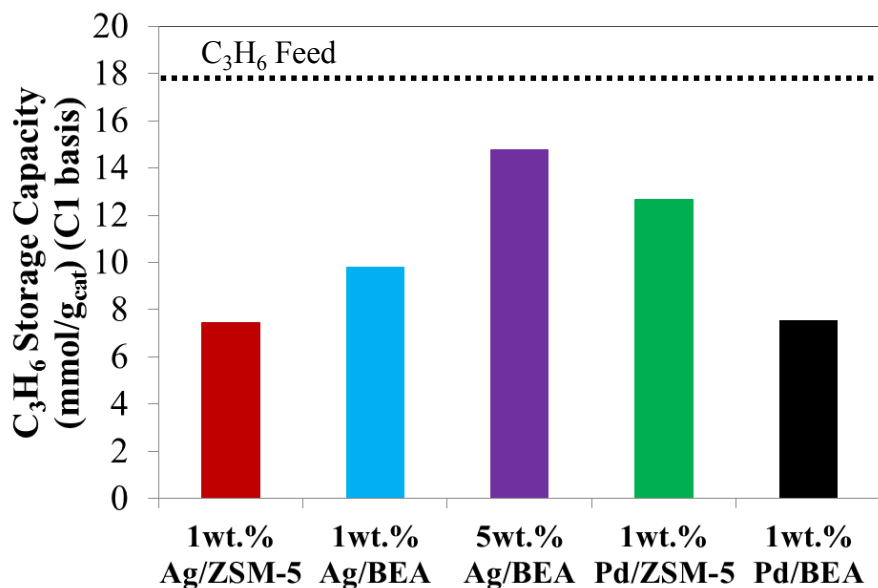
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Adsorption



Combining the HC/NO trap material and the best oxidation catalyst shows pathway to 90% emissions removal at 150°C

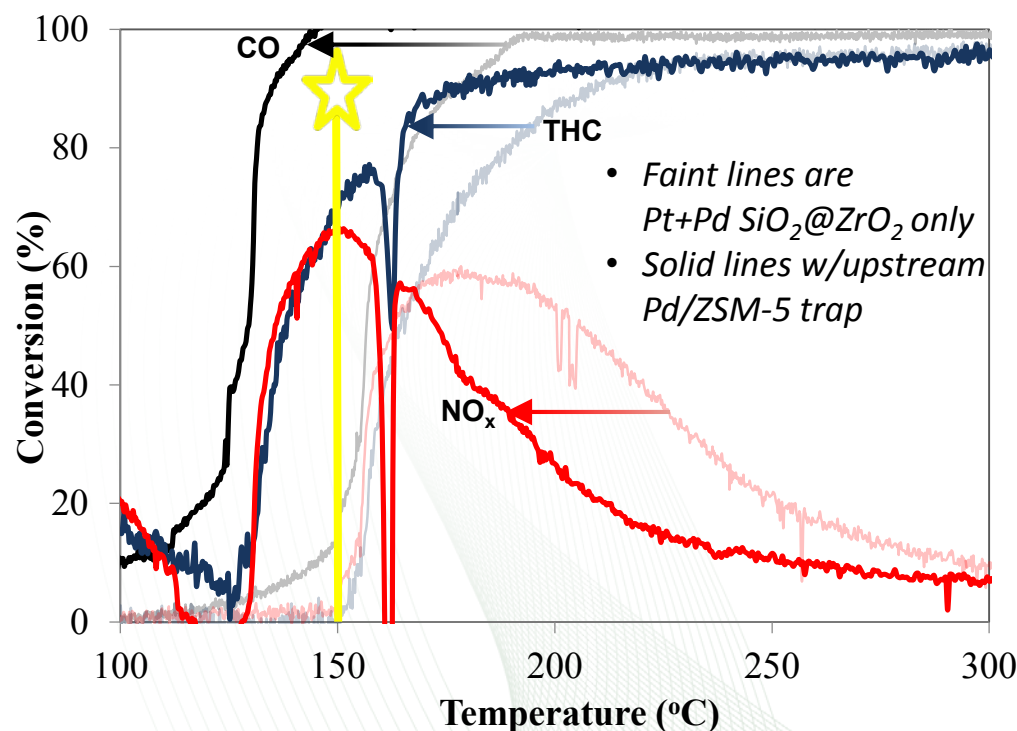
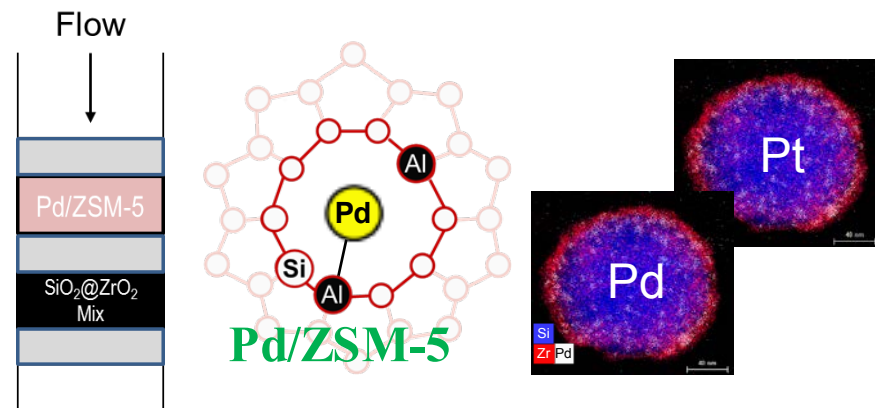
- Experimental conditions

- Dual bed exposure
 - 1st bed Trap: Pd/ZSM-5
 - 2nd bed Pt+Pd SiO₂@ZrO₂ core-shell
 - 1.8%Pt + 0.5%Pd
 - HT-aged at 800°C (2h)
- Reactor at 80°C with liquid LTC-D flowing in bypass (including C₁₀H₂₂)
- Switch flows from bypass to dual bed and immediately begin heating
 - at 5°C/min to 500°C

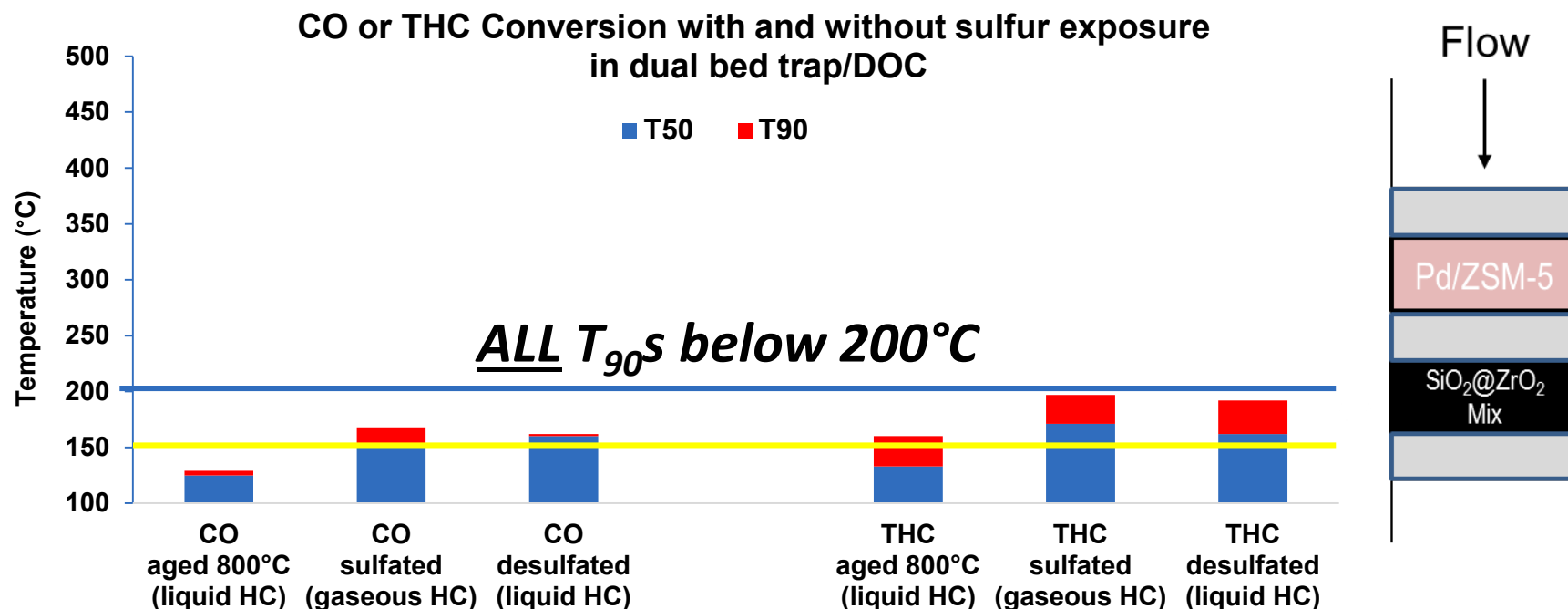
- Trapping of both NO_x and HC results in very low CO light off

- Good NO and HC removal below 150°C, followed by release at 160°C

- Good conversion observed of HC after release



Employing ACEC sulfur protocol in dual bed trap/DOC illustrates excellent tolerance and activity



Sulfation protocol

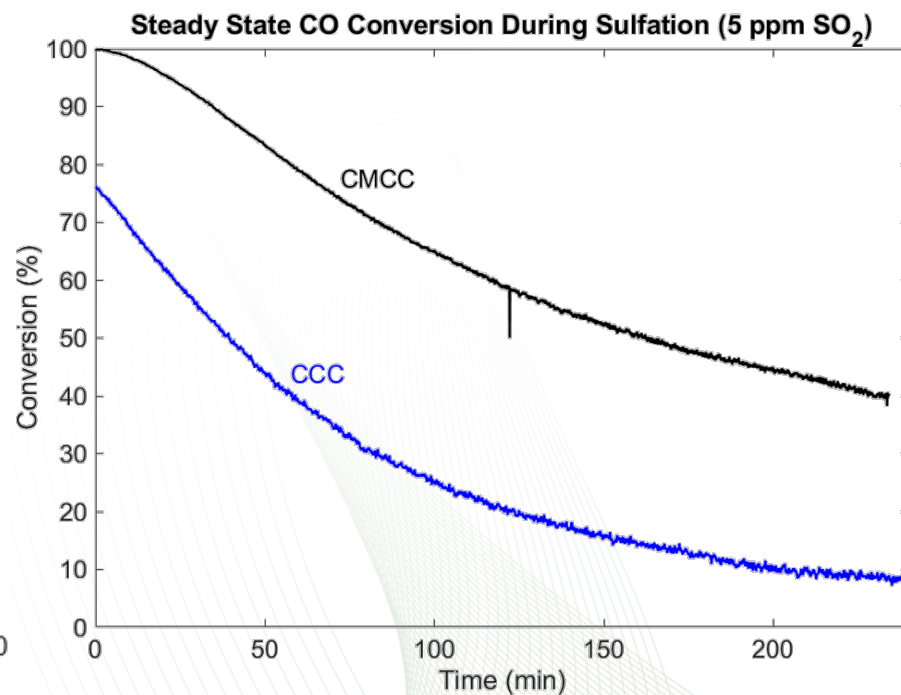
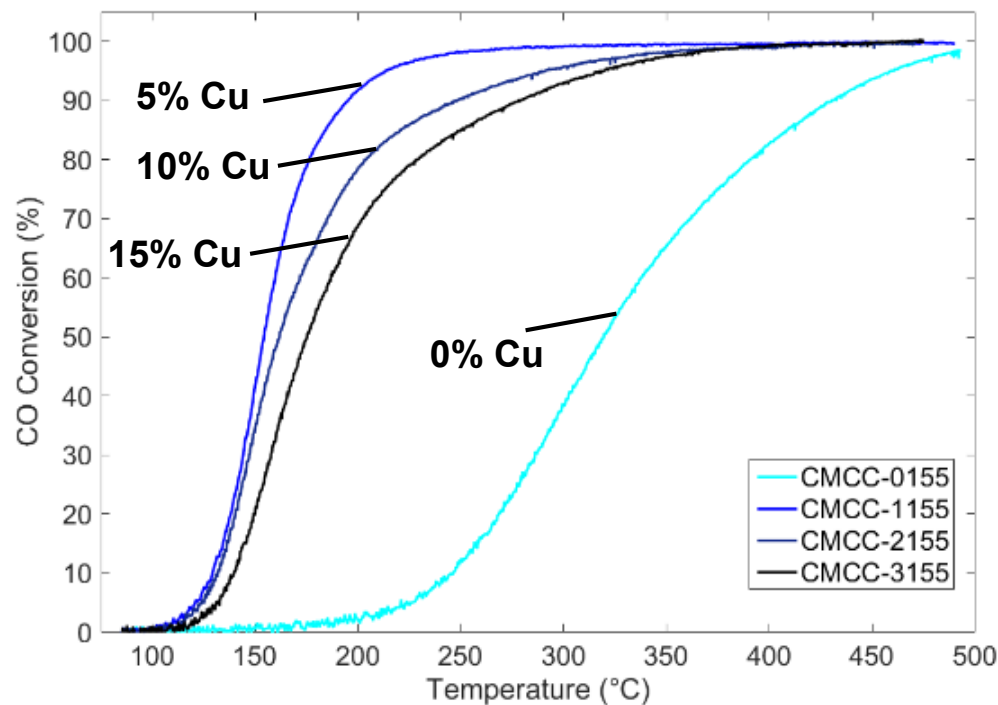
- 5 ppm SO₂ at 300°C for 5 h in full simulated exhaust
- Sulfation and sulfur evaluation performed with gaseous HCs
 - Initial and desulfated evaluation performed with liquid hydrocarbon protocol

Desulfation procedure

- Lean-rich cycling at 500°C for 30 minutes
- Desulfated evaluation starting at 80°C with liquid hydrocarbons

Addition of Mn to CCC formulation improved reactivity of sample under LTC-D conditions; optimal Cu loading found

- Manganese (1%) added to formulation based on interesting low temperature SCR studies
 - Unfortunately no increase in NO to NO₂ oxidation observed (not shown)
- Varying the copper level from 0 to 15% shows that the 1:1:5:5 (Cu:Mn:Co:Ce) ratio illustrates optimal performance



Remaining Challenges

- Support modifications for enhanced PGM activity

PGM content should be as small as possible especially for Pt-containing catalysts

Pt-Pd interactions have been shown to have significant advantages, but whys is this only observed in physical mixtures here?

USC/Solvay collaboration shows excellent initial activity but needs improved durability

- Trapping Materials

Pd/zeolites show excellent effectiveness, but characterization illustrates improved ion-exchanging is necessary

BEA and ZSM-5 zeolites not expected to be hydrothermally stable above 750°C

- PGM-free mixed metal oxides

Unclear if significant role exists for CMCC in combined/dual-bed system

Future Directions

Develop understanding of Pt loading impact on reactivity and durability to enable thrifting of PGM content

Perform extensive bi-metallic materials characterization of the fresh and aged samples to better understand PGM state

Complete aging study on existing catalysts and then explore introduction of optimized metal oxide overlayer

Improve ion-exchange by systematically modifying procedure followed by characterization

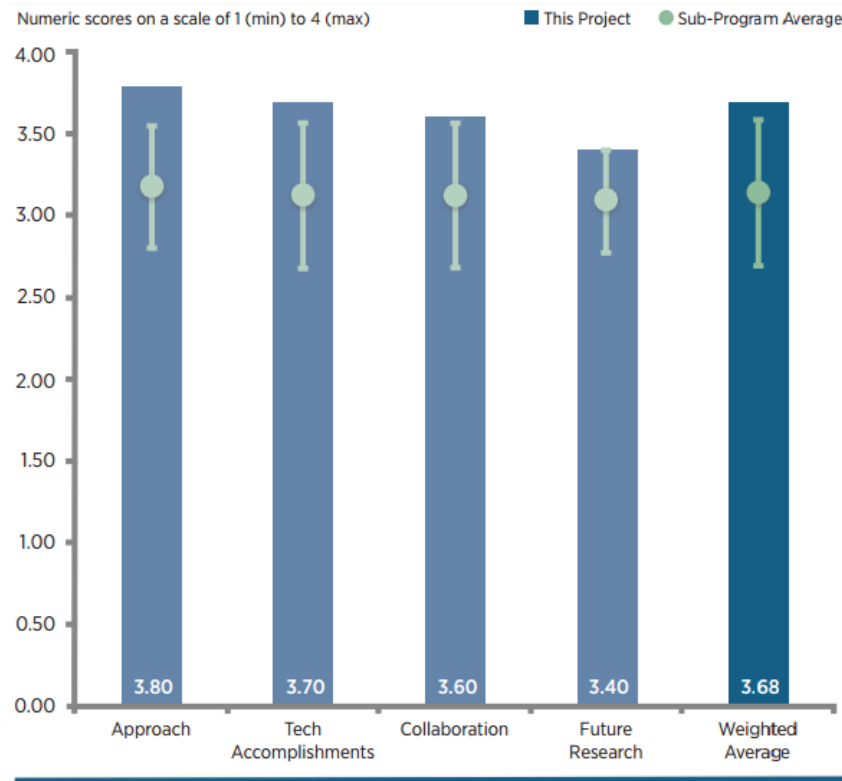
Find failure point of materials plus ones w/ improved ion-exchange; explore CHA; also MECA-member provided materials

Evaluate impact of addition to the dual bed in physical mixture and washcoated with PGM-based oxidation catalysts

Any proposed future work is subject to change based on funding levels

Responses to 2015 Reviewers (5); overall score = 3.68/4.00

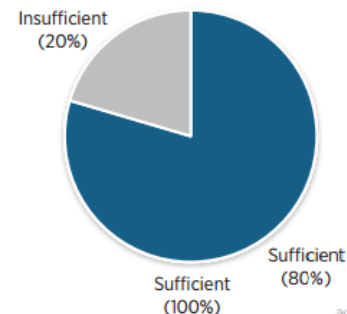
- **Approach (3.8/4.0):** methods used in analyzing the catalytic materials in the project as excellent... **consider HC chains and aromatics ... how does S alter the activity of the catalysts**
- **Technical Accomplishments (3.7/4.0):** very interesting and potentially useful ... **need to understand why PGM inclusion improves S tolerance with CCC** ... commend the project team for considering both thermal aging and S poisoning ... **CO₂ needed in trap evaluations** ... **Rh should be considered for evaluations**
- **Collaborations (3.6/4.0):** interaction with the automotive OEMs and catalyst formulators increases the value of the research ... **OEM would also be a helpful partner**
- **Future plans (3.4/4.0):** future work is appropriate and in line with funding.... sound technical path forward ... **hard to tell if trapping will receive the attention it deserves** ... **effect of sulfur should be the top priority.... Include other HCs**
- **Relevance (100%):** by enabling the use of more efficient combustion, these systems support the move to improving overall fuel economy... low-temperature catalysis is the key barrier to high efficiency combustion strategies
- **Resources (20% Insufficient):** **more resources necessary to meet project and program goals, especially for the NH₃ SCR**



Relevant to DOE Objectives



Sufficiency of Resources



OAK RIDGE
National Laboratory

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ace085

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Responsive Actions

1. **Following LTC-D protocol for liquids this year...aromatics included in new trapping protocol (backup slides)**
2. **S included in all facets this year**

1. **Further research performed in this area for publication, but not major focus**
2. **Examined CO₂ impact in traps; minimal observed, thus removed for C-balance**
3. **Rh catalysts synthesized, but results are not promising to date**

1. **Efforts to coordinate and collaborate with OEMs are ongoing**

1. **Efforts this year give a good balance between trapping and oxidation**
2. **Sulfur included; Pd-traps high tolerance**
3. **Full HC mixture included this year; more in backup slides**

1. **NH₃-SCR evaluation not currently planned; NOx efforts currently focused on adsorber/traps**



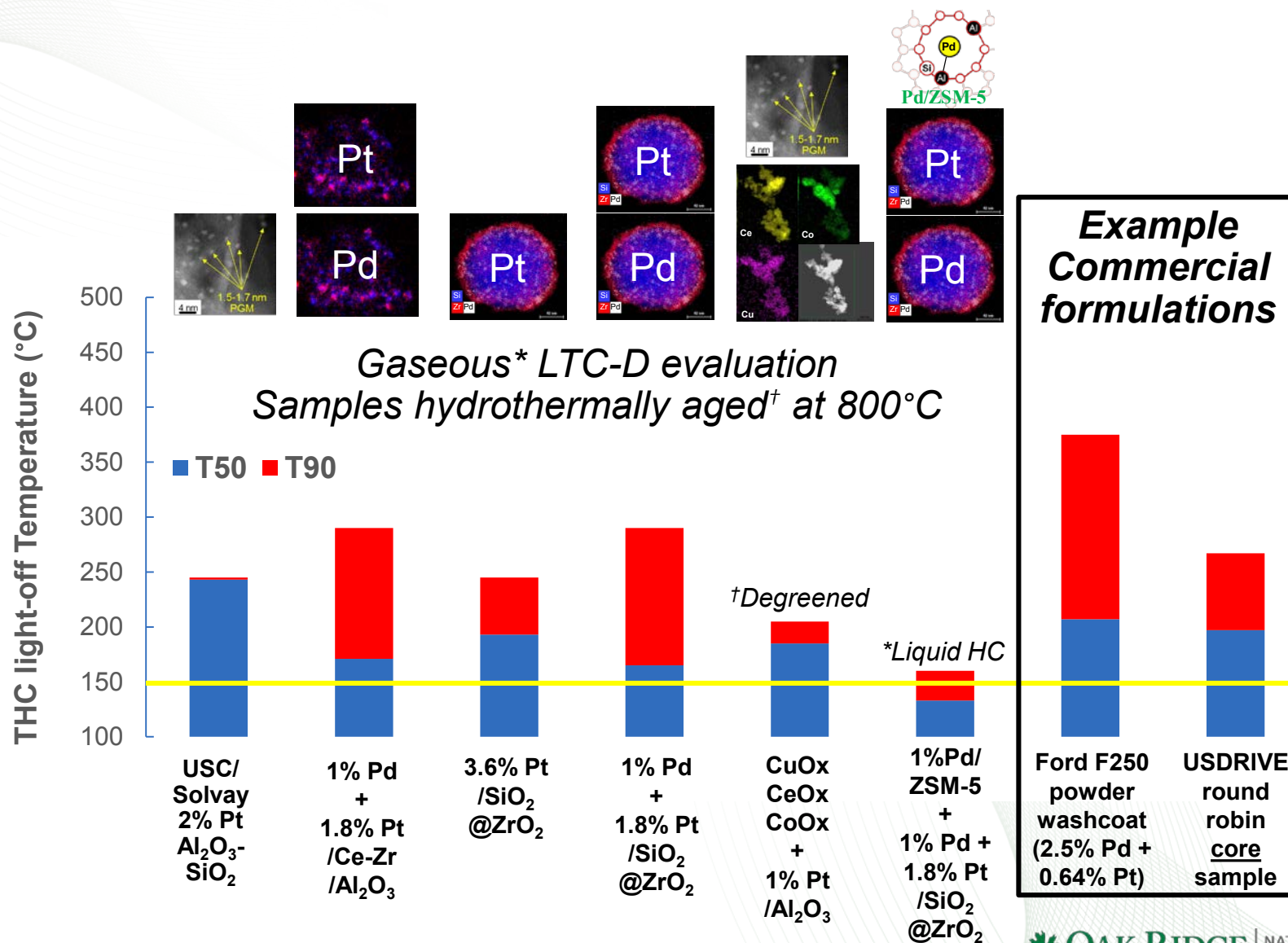
Summary

- **Relevance:** Develop new emission control technologies to enable fuel-efficient engines with low exhaust temperatures ($<150^{\circ}\text{C}$) to meet emission regulations
- **Approach:** employ low temperature protocols to evaluate novel catalysts
- **Collaborations:** Wide-ranging collaboration with industry, academia, & national labs maximizes breadth of study, guides research from other funding sources
- **Technical Accomplishments:**
 - Series of Pt:Pd DOCs synthesized at USC on Solvay supports evaluated & aged at ORNL
 - Physical mixtures of Pt and Pd $\text{SiO}_2@\text{ZrO}_2$ supports show excellent activity with greatly enhanced HC activity
 - Expanded on Ag/zeolite HC/NO trapping studies to include Pd ion-exchanged zeolites
 - Pd/ZSM-5 catalyst shown to have good HC and NOx trapping ability
 - Combining best trap and best DOC showed excellent low temperature behavior and sulfur tolerance
 - Addition of Mn to CCC-based mixed metal oxide significantly improved high space velocity CO activity and sulfur tolerance
- **Future Work:** continued efforts on thriftily optimizing PGM usage, improved durability, and characterization to understand bi-metallic PGM interactions; have internal (ORNL) funding to explore potential commercialization on candidates

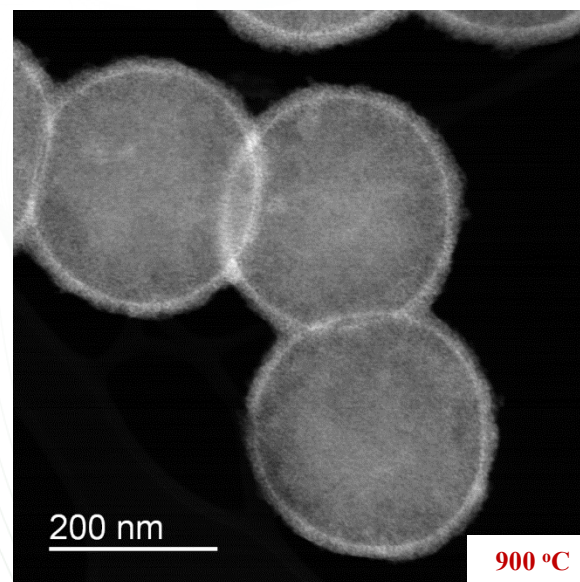
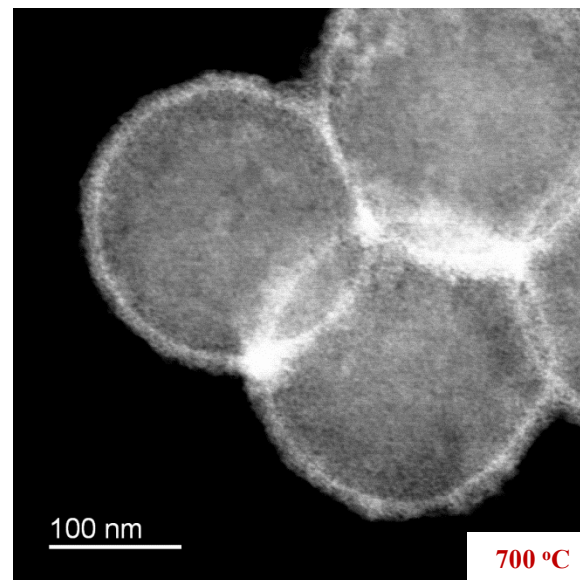
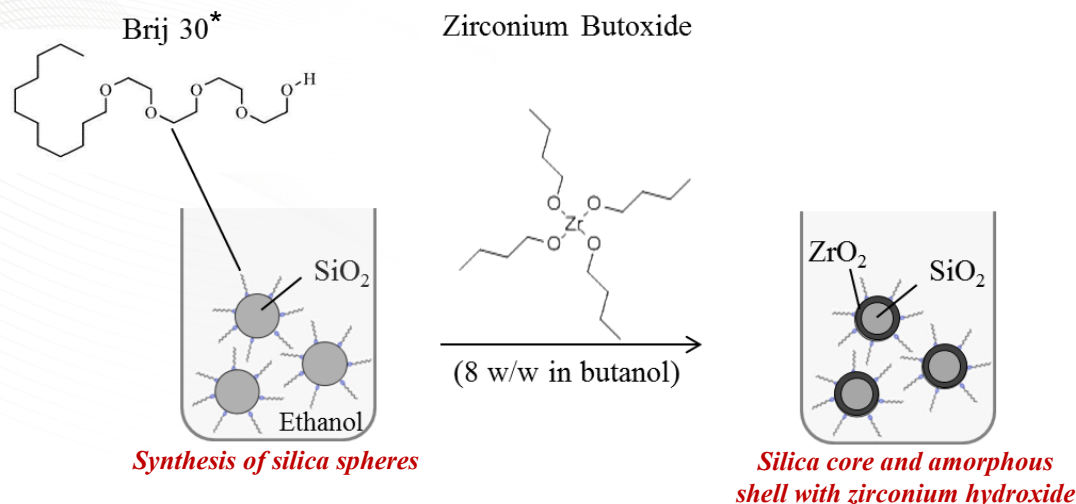
*Any proposed future work is subject to
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Technical Backup Slides

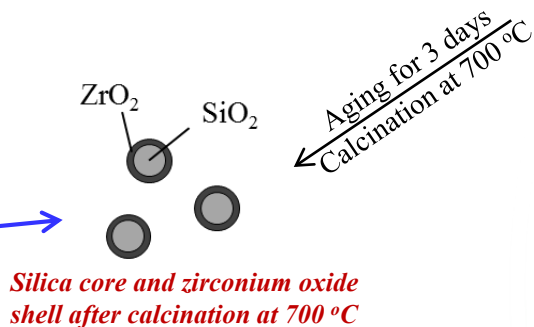
New formulations compare favorably to modern commercial DOCs after HT aging at 800°C



Experiment Detail: Synthesis of SiO₂@ZrO₂ core@shell Oxide Support



Material	Surface Area (m ² /g)
ZrO ₂	97
ZrO ₂ -SiO ₂	153
SiO ₂ @ZrO ₂	210



- SiO₂ is located in the **core** (Si: 14 amu) and **ZrO₂** in the **shell** (Zr: 40 amu).
- The ZrO₂ **shell** seems to be **porous**.
- Growth of SiO₂@ZrO₂ spheres. Shell is maintained. Diameter at: 700 °C: ~220 nm
900 °C: ~250 nm

*(Brij 30): Polyoxyethylene(4) lauryl ether

LTAT Protocol - Storage

Table 2 – Step 1 of protocol: Pre-treatment

PRE-TREATMENT – CDC, LTC-D, LTC-G, L-GDI									
Step No.	Temperature	Exhaust make-up (balance N ₂)*							Bypass
LTP-2-1P	Pretreat 20 min @ 600°C	-	-	-	-	[O ₂]	[H ₂ O]	[CO ₂]	Off
LTP-2-2P	Cool 600°C to 100°C	-	-	-	-	[O ₂]	[H ₂ O]	[CO ₂]	Off
LTP-2-3P	Hold 5 min @ 100°C	-	-	-	-	[O ₂]	[H ₂ O]	[CO ₂]	Off
PRE-TREATMENT – S-GDI									
Step No.	Temperature	Exhaust make-up (balance N ₂)*							Bypass
LTP-2-1PS	Pretreat 20 min @ 600°C	-	-	-	-	[O ₂]	[H ₂ O]	[CO ₂]	Off
LTP-2-2PS	Cool 600°C to 350°C	-	-	-	-	-	[H ₂ O]	[CO ₂]	Off
LTP-2-3PS	Reduce 5 min @ 350°C	-	3% CO	1% H ₂	-	-	[H ₂ O]	[CO ₂]	Off
LTP-2-4PS	Cool 350°C to 100°C	-	-	-	-	-	[H ₂ O]	[CO ₂]	Off
LTP-2-5PS	Hold 5 min @ 100°C	-	-	-	-	-	[H ₂ O]	[CO ₂]	Off

* Bracketed concentration values are combustion-mode dependent and found in Table 1

Table 3 – Step 2 of protocol: Storage

STORAGE – all modes									
Step No.	Temperature	Exhaust make-up (balance N ₂)*							Bypass
LTP-2-3S	Hold 100°C	[HC]	[CO]	[H ₂]	[NO]	[O ₂]	[H ₂ O]	[CO ₂]	On
LTP-2-4S	Hold 100°C for 30 min	[HC]	[CO]	[H ₂]	[NO]	[O ₂]	[H ₂ O]	[CO ₂]	Off

* Bracketed concentration values are combustion-mode dependent and found in Table 1

** For inlet characterization; dependent on time required to stabilize inlet concentrations

Table 4 – Step 3 of protocol: Release (and/or conversion)

NO _x RELEASE – all modes									
Step No.	Temperature	Exhaust make-up (balance N ₂)*							Bypass
LTP-2-SRN	Ramp 20°C/min to 600°C	-	-	-	[NO]	[O ₂]	[H ₂ O]	[CO ₂]	Off
HC RELEASE – CDC, LTC-D, LTC-G, L-GDI									
Step No.	Temperature	Exhaust make-up (balance N ₂)*							Bypass
LTP-2-SRH	Ramp 20°C/min to 600°C	-	-	-	[NO]	[O ₂]	[H ₂ O]	[CO ₂]	Off
HC RELEASE – S-GDI									
Step No.	Temperature	Exhaust make-up (balance N ₂)*							Bypass
LTP-2-SRHS	Ramp 20°C/min to 600°C	-	-	-	-	-	[H ₂ O]	[CO ₂]	Off

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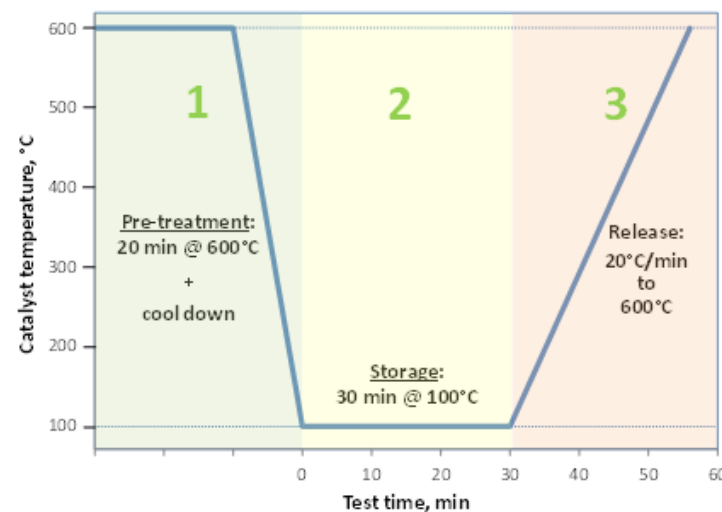


Figure 3 – Storage protocol temperature control

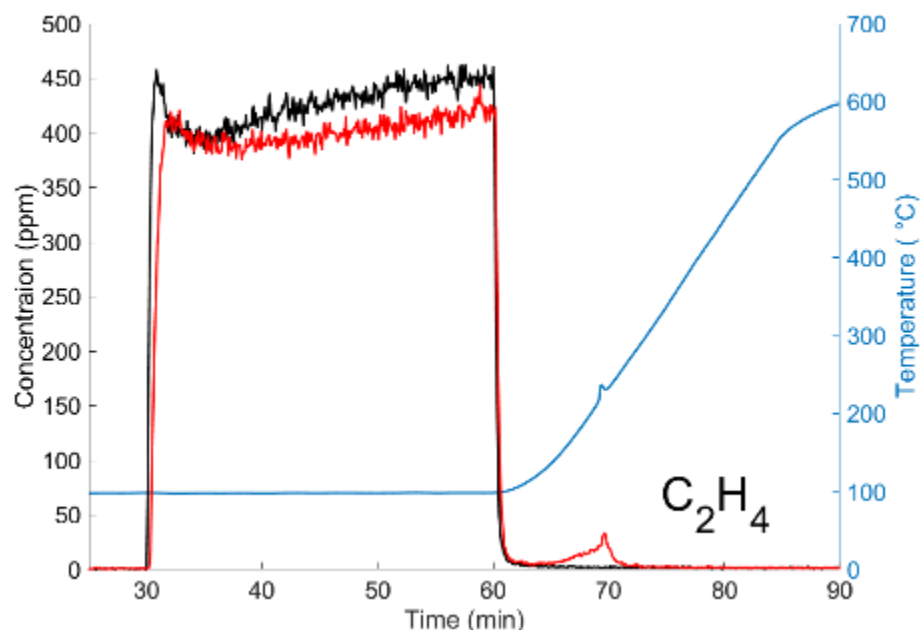
Table 5 – Catalyst de-greening parameters

S-GDI, L-GDI, LTC-G					
Step No.	Mode	Condition	Exhaust make-up (balance N ₂)		
			[O ₂]	[CO ₂]	[H ₂ O]
LTP-1DG-G	Neutral	700°C/4 hours	-	10%	10%
CDC, LTC-D					
Step No.	Mode	Condition	Exhaust make-up (balance N ₂)		
			[O ₂]	[CO ₂]	[H ₂ O]
LTP-1DG-D	Lean	700°C/4 hours	10%	5%	5%

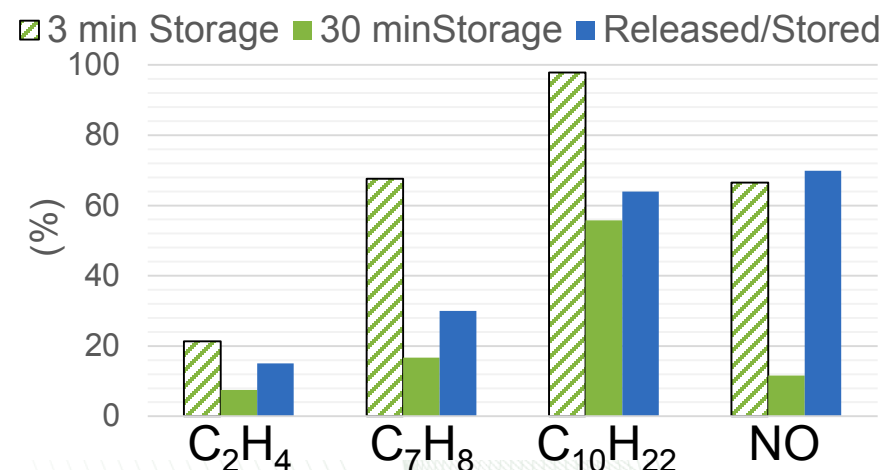
Employing ACEC storage protocol in future trapping experiments with liquid hydrocarbons

- ACEC Low-Temperature Storage Catalyst Test Protocol (in draft phase) calls for 30 minutes of storage at 100 °C with multiple liquid hydrocarbon species as well as standard exhaust gasses (CO, NO, H₂, etc...)
- Pd/ZSM-5 stores a considerable amount of NO, toluene and decane with a peak release centered around 210 °C

Pd/ZSM-5 Storage and Ramp



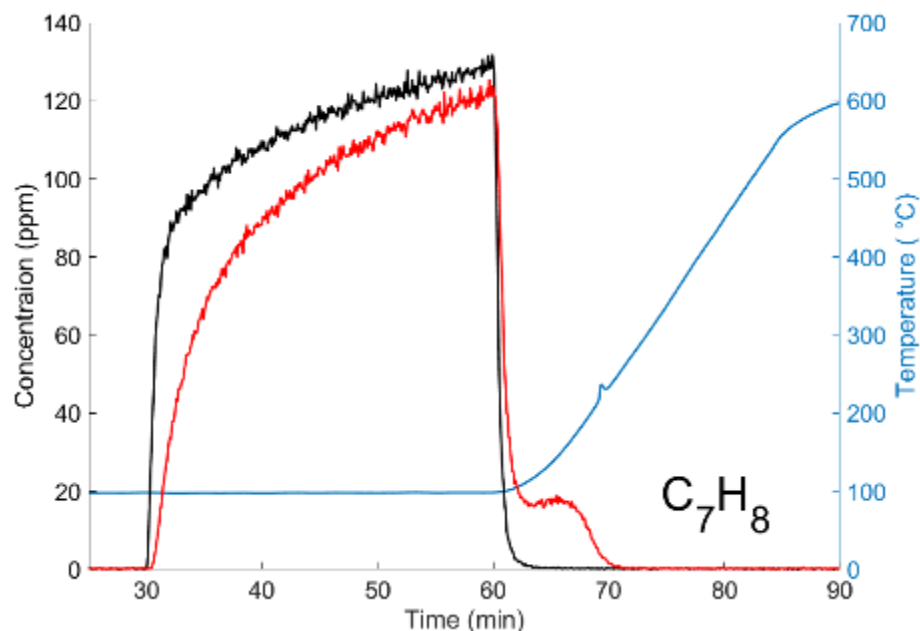
	C ₂ H ₄	C ₇ H ₈	C ₁₀ H ₁₂	NO
Total Stored (mg/g _{cat})	2.11	4.43	21.32	0.78
3 min storage (mg/g _{cat})	0.52	0.95	2.04	0.45



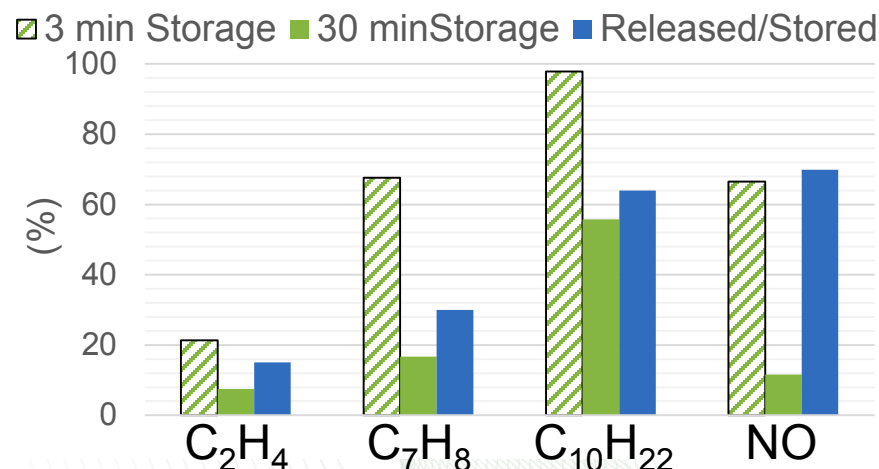
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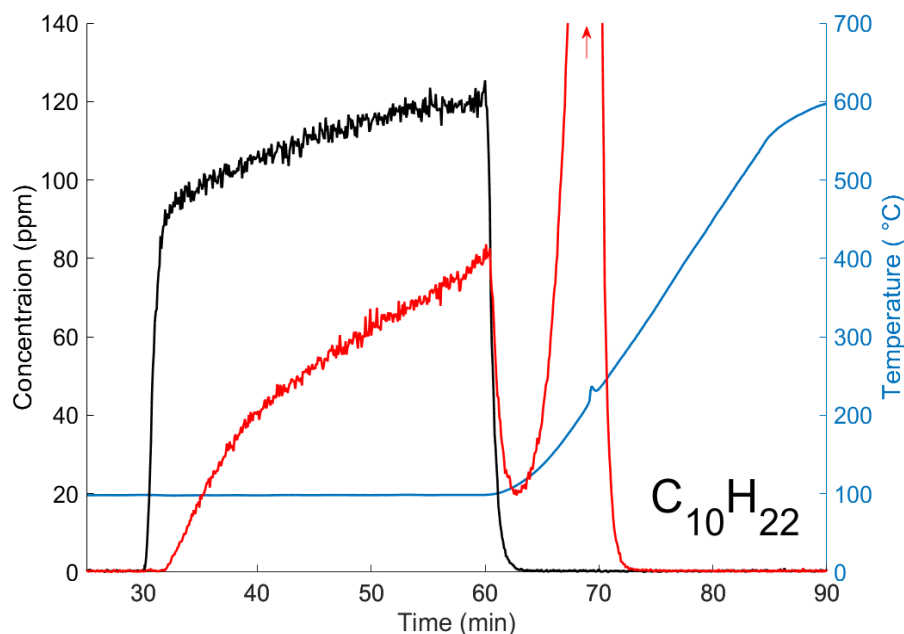
	C_2H_4	C_7H_8	$C_{10}H_{12}$	NO
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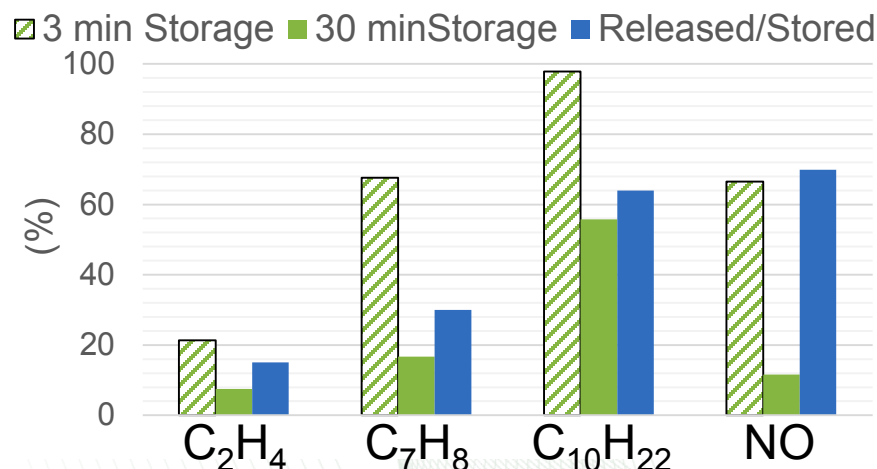
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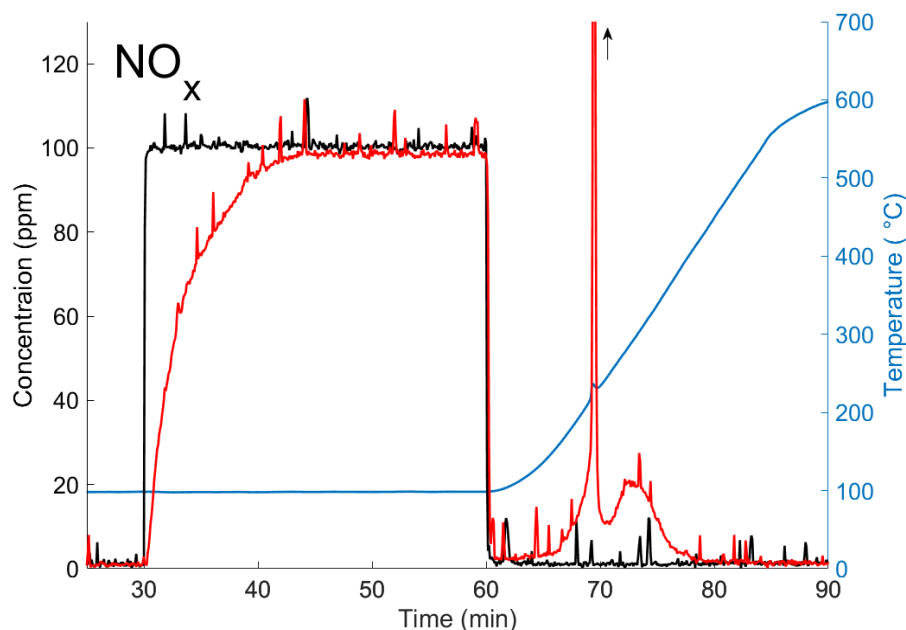
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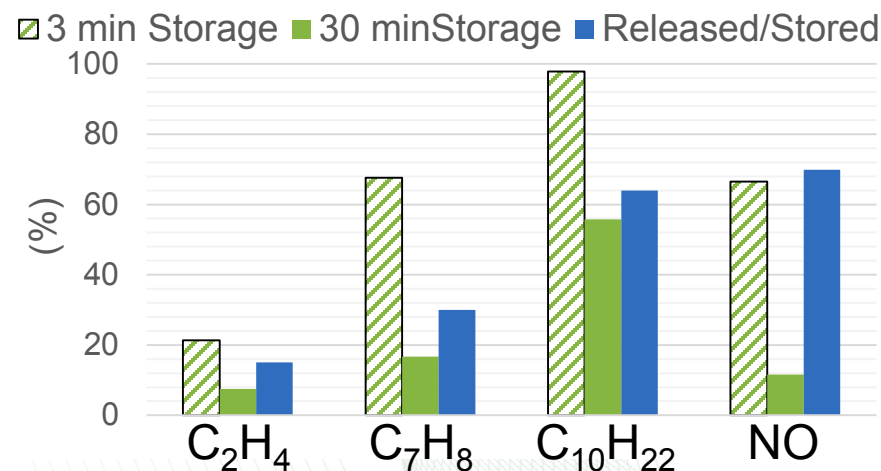
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CCC by Glycine-Nitrate “Combustion” Synthesis Shows Increased Surface Area and Performance for Lean Exhaust



- CCC was synthesized by glycine-nitrate process (metal nitrates mixed with glycine and brought to auto-combustion temperature). This process is more easily scalable than co-precipitation and results in a fine powder with a nearly 10 fold increase in apparent volume at 100 mg, suggesting greatly increased surface area.
- Resulting degreened CCC powder shows lower T_{90} temperatures for CO conversion and greatly increased HC performance during LTC-D exhaust testing. This is likely a result of the greatly enhanced surface area of the catalyst.

